Analysis of the risk associated to coastal flooding hazards: A new historical extreme storm surges dataset for Dunkirk, France

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Abstract

This paper aims to demonstrate the technical feasibility of a historical study devoted to French Nuclear Power Plants (NPPs) which can be prone to extreme coastal flooding events. It has been shown in the literature that the use of Historical Information (HI) can significantly improve the probabilistic and statistical modeling of extreme events. There is a significant lack of historical data on marine flooding (storms and storm surges) compared to river flooding events. To address this data scarcity and to improve the estimation of the risk associated with coastal flooding hazards, a dataset of historical storms and storm surges that hit the Nord-Pas-de-Calais region during the past five centuries was created from archival sources, examined and used in a frequency analysis (FA) in order to assess its impact on frequency estimations. This work on the Dunkirk site (representative of the Gravelines NPP) is a continuation of previous work performed on the La Rochelle site in France. Indeed, the frequency model (FM) used in the present paper had some success in the field of coastal hazards and it has been applied in previous studies to surge datasets to prevent coastal flooding in the La Rochelle region in France.

In a first step, only information collected from the literature (published reports, journal papers and PhD theses) is considered. Although this first historical dataset has extended the gauged record back in time to 1897, serious questions related to the exhaustiveness of the information and about the validity of the developed FM have remained unanswered. Additional qualitative and quantitative HI was extracted in a second step from many older archival sources. This work has led to the construction of storms and coastal flooding sheets summarizing key data on each identified event. The quality control and the cross-validation of the collected information, which have been carried out systematically, indicate that it is valid and complete as regards extreme storms and storm surges. Most of the HI collected is in good agreement with other archival sources and documentary climate reconstructions. The probabilistic and statistical analysis of a dataset containing an exceptional observation considered as an outlier (i.e. the 1953 storm surge) is significantly improved when the additional HI collected in both literature and archives is used. As the historical data tend to be extreme, the right tail of the distribution has been reinforced and the 1953 "exceptional" event does not appear as an outlier any more. This new dataset provides a valuable source of information on storm surges for future characterization of coastal hazards.

Key-words: Coastal storms; Storm surges; Coastal flooding; Historical information; Frequency analysis;

1 Introduction

As the coastal zone of the Nord-Pas-de-Calais region in Northern France is densely populated, coastal flooding represents a natural hazard threatening the costal populations and facilities in several areas along the shore. The Gravelines Nuclear Power Plant (NPP) is one of those coastal facilities. It is located near the community of Gravelines in Northern France, approximately 20 km from Dunkirk and Calais. The Gravelines NPP is the sixth largest nuclear power station in the world, the second largest in Europe and the largest in Western Europe.

Extreme weather conditions could induce strong surges that could cause coastal flooding. The 1953 North Sea flood was a major flood caused by a heavy storm that occurred on the night of Saturday, 31 January and morning of Sunday, 1 February. The floods struck many European countries and France had not been the exception. This was particularly the case along the northern coast of France, from Dunkirk to the Belgium border. Indeed, it has been shown in an unpublished study that Dunkirk is fairly representative of the Gravelines NPP in terms of extreme sea levels. In addition, the harbor of Dunkirk is an important military base containing a lot of archives. The site of Dunkirk has therefore been selected as site of interest in the present paper (Fig. 1). An old map of Dunkirk city is presented in the right panel of Fig. 1 (we shall return to this map at a later stage in this paper). It is a common belief today that the Dunkirk region is vulnerable and subject to several climate risks (e.g. Maspataud et al. 2013). More severe coastal flooding events such as the November 2007 North Sea and the March 2008 Atlantic storms could have had much more severe consequences especially if they had occurred at hightide (Maspataud et al. 2013; Idier et al. 2012). It is important for us to take into account the return periods of such events (especially in the current context of global change and projected sea-level rise) in order to manage and reduce coastal hazards, implement risk prevention policies and enhance and strengthen coastal defence against coastal flooding.

The storm surge frequency analysis (FA) represents a key step in the evaluation of the risk associated with coastal hazards. The frequency estimation of extreme events (induced by natural hazards) using probability functions has been extensively studied for more than a century (e.g. Gumbel, 1935; Chow, 1953; Dalrymple, 1960; Hosking and Wallis, 1986, 1993, 1997, Hamdi et al. 2014, 2015). We generally need to estimate the risk associated with an extreme event in a given return period. Most extreme value models are based on available at-site recorded observations only. A common problem in FA and estimation of the risk associated with extreme events is the estimation from a relatively short gauged record of the flood corresponding to 100-1000 year return periods. The problem is even more complicated when this short record contains an outlier (an observation much higher than any others in the dataset). This is the case with several sea-level time series in France and characterizes the Dunkirk surge time series as well.

The 1953 storm surge was considered as an outlier in our previous work (Hamdi et al, 2014) and in previous research (e.g. Bardet et al, 2011). Indeed, although the Gravelines NPP is designed to sustain very low probabilities of failure and despite the fact that no damage was reported at the French NPPs, the 1953 coastal flooding had shown that the extreme sea levels estimated with the current statistical approaches could be underestimated. It seems that the local FA is not really suitable for a relatively short dataset containing an outlier.

Indeed, a poor estimation of the distribution parameters may be related to the presence of an outlier in the sample (Hamdi et al, 2015), and must be properly addressed in the FA. One would expect that one or more additional extreme events in a long period (500 years for instance) would, if properly included in the frequency model (FM), improve the estimation of a quantile at the given high-return period. The use of other sources of information with more appropriate FMs is required in the frequency estimation of extremes. Worth noting is that this recommendation is not new and dates back several years. The value of using other sources of data in the FA of extreme events has been recognized by several authors (e.g. Hosking and Wallis, 1986 and Stedinger and Cohn, 1986). By other sources of information we refer here to events that occurred not only before the systematic period (gauging period) but also during gaps of the recorded time series. Water marks left by extreme floods, damage reports and newspapers are reliable sources of Historical Information (HI). It can also be found in the literature, archives, unpublished written records, etc. It may also arise from verbal communications from the general public. Paleoflood and dendrohydrology records (the analysis and application of tree-ring records) can be useful as well. A literature review on the use of HI in flood FAs with an inventory of methods for its modeling has been published by Ouarda et al, (1998). Attempts to evaluate the usefulness of HI for the frequency estimation of extreme events are numerous in the literature (e.g. Guo and Cunnane, 1991; Ouarda et al, 1998; Gaal et al, 2010; Payrastre et al, 2011; Hamdi, 2011; Hamdi et al, 2015). Hosking and Wallis (1986) have assessed the value of HI using simulated flood series and historical events generated from an extreme value distribution and quantiles are estimated by the maximum likelihood method with and without the historical event. The accuracy of the quantile estimates was then assessed and it was concluded that HI is of great value provided either that the flood frequency distribution has at least three unknown parameters or that gauged records are short. It was also stated that the inclusion of HI is unlikely to be useful in practice when a large number of sites are used in a regional context. Because HI is often imprecise, its inaccuracy should be considered in the analysis. Nevertheless, the influence of an outlier can be decreased by increasing its representativity in the sample when using the HI, knowing that its uncertainty is sometimes considerable (e.g. Payrastre et al, 2011; Hamdi et al, 2015). A frequency estimation of extreme storm surges based on the use of HI has rarely been studied explicitly in the literature (Bulteau et al, 2014, Hamdi et al, 2015, 2016) despite its significant impact on social and economic activities and on NPPs' safety. Bulteau et al. (2014) have estimated extreme sea-levels by applying a Bayesian model to the La Rochelle site in France. This same site was used as a case study by Hamdi et al, (2015) to characterize the coastal flooding hazard. The use of a skew surge series containing an outlier in local frequency estimation is limited in the literature as well. For convenience, we would like to recall here the definition of a skew surge: It is the difference between the maximum observed water level and the maximum predicted tidal level regardless of their timing during the tidal cycle (a tidal cycle contains one skew surge).

It is often possible to augment the storm surges record with those that occurred before and after gauging began. Before embarking on a thorough and exhaustive research of any HI related to coastal flooding that hit the area of interest, potential sources of historical coastal flooding data for the French coast (Atlantic and English Channel) and more specifically for the Charente-Maritime region were identified in the literature (e.g. Garnier and Surville, 2010). The HI collected has been very helpful in the estimation of extreme surges at La Rochelle, which was heavily affected by the storm Xynthia in 2010 that generated a water level considered so far as an outlier (Hamdi et al, 2015). Indeed, these results for the La Rochelle site have encouraged us to build a more complete historical database covering all the extreme coastal flooding that occurred over the past five centuries on the entire French coast (Atlantic and English Channel). This database has been completed and is currently the subject of a working group involving several French organizations for maintenance. However, only the historical storm surges that hit the Nord-Pas-de-Calais region during this period are presented herein.

The main objective of the present work is the collection of HI on storms and storm surges that occurred in the last five centuries and to examine its impact on the frequency estimation of extreme storm surges. The paper is organized as follows: HI collected in the literature and its impact on the FA results is presented in sections 2 and 3. The fourth section presents the HI recovered from archival sources, the quality control thereof, and validation. In section 5, the FM is applied using both literature and archival sources. The results are discussed in the same section before concluding and presenting some perspectives in section 6.

2 Use of HI to improve the frequency estimation of extreme storm surges

The systematic storm surge series is obtained from the corrected observations and predicted tide levels. The tide gauge data is managed by the French Oceanographic Service (SHOM - Service Hydrographique et Océanographique de la Marine) and measurements are available since 1956. The R package TideHarmonics (Stephenson, 2015) is used to calculate the tidal predictions. In order to remove the effect of sea level rise, the initial mean sea level (obtained by tidal analysis) is corrected for each year by using an annual linear regression, before calculating the predictions. The regression is obtained by calculating daily means using a Demerliac Filter (Simon 2007). Monthly and annual means are calculated with respect to the Permanent Service for Mean Sea Level (PSMSL) criteria (Holgate, et al, 2013). This method is inspired by the method used by SHOM for its analysis of high water levels during extreme events (SHOM, 2015). The available systematic surge dataset was obtained for the period from 1956 to 2015.

The effective design of coastal defense is dependent on how high a design quantile (1000-year storm surge for instance) will be. But this is always estimated with uncertainty and not precisely known. Indeed, any frequency estimation is given with a confidence interval (CI) of which the width depends mainly on the size of the sample used in the estimation. Some other sources of uncertainties (such as the use of trends related to climate change) can be considered in the frequency estimation (Katz et al, 2002). As mentioned in the introductory section, samples are often short and characterized by the presence of outliers. The CIs are rather large and in some cases more than 2 or 3 times (and even more) the value of the quantile. Using the upper limit of this CI would likely lead to a more expensive design of the defense structure. One could just use the most likely estimate and neglect the CI but it is more interesting to consider the uncertainty as often estimated in frequency analyses. The width of the CI (i.e. inversely related to the sample size) can be reduced by increasing the sample size. In the present work, we focus on increasing the number of observations by adding information about storm surges induced by historical events. Additional storm surges can be subdivided into two groups:

1. HI during gaps in systematic records;
2. HI before the gauging period (can be found in the literature and/or collected by historians in archives).

3 HI during and before the gauging period

A historical research devoted to the French NPPs located on the Atlantic and English Channel coast was a genuine scientific challenge due to the time factor and the geographic dispersion of the nuclear sites. To be considered in the FA, a historical storm surge must be well documented; its date must be known and some information on its magnitude must be available. Mostly, available information concerns the impact and the societal disruption caused at the time of the event (Baart, 2011).

3.1 HI collected in the literature

As mentioned above, a common issue in frequency estimations is the presence of gaps within the datasets. Failure of the measuring devices and damage, mainly caused by natural hazards (storms, for instance), are often the origin of these gaps. Human errors, strikes, wars, etc., can also give rise to these gaps. Nevertheless, these gaps are themselves considered as dependent events. It is therefore necessary to ensure that the occurrence of the gaps and the observed variable are independent. Whatever the origin and characteristics of the missing period, the use of the full set of extreme storm surges that occurred during the gaps is strongly recommended to ensure the exhaustiveness of the information. This will make the estimates more robust and reduce associated uncertainties. Indeed, by delving into the literature and the web, one can obtain more information about this kind of events. Maspataud (2011) was able to collect sea-level measurements that were taken by regional maritime services during a storm event in the beginning of 1995, a time where the Dunkirk tide gauge was not working. This allowed the calculation of the skew surge, which was estimated by the author at 1,15m on January 2nd, 1995. This storm surge is high enough to be considered as an extreme event. In fact, it was exceeded only twice during the systematic period (January 5th, 2012 and December 6th, 2013).

For the relatively short-term pre-gauging period, a literature review was conducted in order to get an overview of the storm events and associated surges that hit the Nord-Pas-de-Calais region in France during the last two centuries. Some documents and storm databases on local, regional or national scales are available:

- the "Plan de Prévention de Risques Littoraux (PPRL)": refers to documents made by the French state on a communal scale, describing the risks a coastal zone is subject to, e.g. coastal flooding and erosion, and preventive measures in case of a hazard happening. To highlight the vulnerability of a zone, an inventory of storms and marine inundation within the considered area is attached to this document;
- Deboudt (1997) and Maspataud (2011) describe the impact of storms on coastal areas for the study region;
- the VIMERS Project: gives information on the evolutions of the Atlantic depressions that hit Brittany (DREAL Bretagne 2015);
- NIVEXT Project: presents historical tide gauge data and the corresponding extreme water and surge levels for storm events (SHOM, 2015);
- Lamb 1991: provides synoptic reconstructions of the major storms that hit the British Isles from the 16th century up till today.

According to the literature, the storm of January 31st to February 1st, 1953 caused the greatest surge and was the most damaging within the study area. This event has been well analyzed and documented (Sneyers, 1953, Rossiter 1954, Gerritsen, 2005, Wolf and Flather 2005): A depression formed over the Northern Atlantic Ocean close to Iceland moving eastward over Scotland and then changing its direction to south-eastwards over the North Sea, accompanied by strong northerly winds. An important surge was generated by this storm that, in conjunction with a high springtide, resulted in particularly high sea levels. Around the southern parts of the Northern Sea the maximum surges exceeded 2.25m, reaching 3.90m at Harlingen, Netherlands. Large areas were flooded in Great Britain, northern parts of France, Belgium, the Netherlands and the German Bight, causing the death of more than 2,000 people. Le Gorgeu and Guitonneau (1954) indicate that during this event, the water level exceeded the predicted water level at the Eastern Dyke of Dunkirk by more than 2.40m (Table 1). Bardet et al. (2011) included a storm surge equal to 2.13m in their regional frequency analysis. Both authors indicate the same observed water level, i.e. 7.90m, but the predicted water level differs: While in 1954 the predicted water level was estimated at 5.50m, the predictions were reevaluated to 5.77m by the SHOM using the harmonic method. A storm surge of 2.13m is therefore used in the present study. Nevertheless, as also shown in Table 1, some other storms (1897, 1949 and 1995) inducing important storm surges and coastal floods occurred within the area of interest. Appendix 1 presents a description of these events which are quite well documented in the literature. In the appendix, the description of some other historical events (of which the information provided did not allow the estimation of a storm surge value) is included as well.

3.2 HI collected in the archives

For the longer term, the HI collection process involves the exploration and consultation, in a context of a permanent multi-scalar approach, of HI which can be seen as a real documentary puzzle with a large number of historical sources and archives. Indeed, NPPs are generally located, for obvious safety reasons, in sparsely populated and isolated areas which is why these sites were subject to little anthropogenic influence in the past. However, this difficulty does not forfeit a historical perspective due to the rich documentary resources for studying an extreme event on different scales ranging from the site itself to that of the Region (Garnier, 2015 and 2017 a). In addition, this may be an opportunity for researchers and a part of the solution because it also allows a risk assessment at ungauged sites.

First, it is important to distinguish between "direct data" (also referred to as "direct evidence") and "indirect data" (also referred to as "proxy data"). The first refers to all information from the archives that describes an extreme event (a storm surge event for instance) that occurred at a known date. If their content is mostly instrumental, such as meteorological records presented in certain ordinary books or by the Paris Observatory (since the 17th century), sometimes accurate descriptions of extreme climatic events are likewise found. The "proxy data" rather indicate the influence of certain storm initiators and triggers such as wind and pressure. Concretely, they provide information indirectly on coastal flooding for example.

Private documents or "ego-documents" (accounts and ordinary books, private diaries, etc.) are used in many ways during 16th to 19th centuries. Authors recorded local facts, short news and latest events, and amongst them, weather incidents. These misidentified historical objects may contain many valuable meteorological data. These private documents most often take the form of a register or a journal in which the authors record various events (economic, social and political) as well as weather information. Other authors use a more integrated approach to describe a weather event by combining observations of extreme events, instrumental information, phenology (impact on harvests), prices in local markets and possibly its social expression (scarcity, emotions, riots, etc.). All these misidentified sources are another opportunity for risk and climate historians to better understand the natural and coastal hazards (coastal flooding, earthquakes, tsunamis, landslides, etc.) of the past. Some of these private documents may be limited to weather tables completely disconnected from their socio-economic and climatic contexts. Most of the consulted documents and archives describe the history of coastal flooding in the area of interest. Indeed, the historical inventory identifies and describes damaging coastal flooding that occurred on the northern coast of France (Nord-Pas-de-Calais and Dunkirk) over the past five centuries. It presents a selection of remarkable marine floods that occurred in this area and integrates not only old events but also those occurring after the gauging period began. The information is structured around storms and coastal flooding summary sheets. Accompanied and supported by a historian, several research and field missions were carried out and a large number of archival sources explored and, whenever possible, exploited. The historical analysis began with the consultation of the documentary information stored in the rich library of the communal archive of Dunkirk, Gravelines, Calais and Saint-Omer. The most consulted documents were obtained directly from the Municipal archives because the Municipal Acts guarantee a chronological continuity at least from the end of the 16th century up to the French Revolution (1789). Very useful for spotting extreme events, they unfortunately provide poor instrumental information. We therefore also considered data from local chronicles of annals of the city of Dunkirk, as well as reports written by scientists or naturalists to describe tides at Calais, Gravelines, Dunkirk, Nieuport and Oostende. Most of them contain old maps, technical reports, sketches or plans of dykes, sluices and docks designed by engineers of the 18th to 20th centuries and from which it may be possible to estimate water levels reached during extreme events. Bibliographical documents are mostly chronicles, annals and memoirs written after the disaster. Finally, for the more recent period, available local newspapers were consulted.

Multiplying the sources and trying to crosscheck events allowed us to constitute a database of 73 events. We focused the research on the period between 1500 and 1950, since most of the time tide gauge observations are available after 1950. The first event took place in 1507 and the last in 1995. Depending on how it is mentioned in the archive and as shown in the left panel of Fig. 2, the collated events were split in two groups. Storm surge events are events where there is a clear mention of flooding within the sources. Are considered as storms, events where only information about strong wind and gales are available. Except for the 19th century, we have much more storm surge events than storms events. All the collected events are summarized in Table 2.

3.3 Data quality control

First of all, it is appropriate to remember that the storm surge is the variable of interest in our historical research. It should, however be stressed here that the total sea level, as it is a more operational information, is likely to be available most often. The conversion to the storm surge is performed afterwards by subtracting the predicted levels (which are calculated using the tide coefficients). Nevertheless, all types of data require quality control and need to be corrected and homogenized if necessary to ensure that the data are reflecting real and natural variations of the studied phenomena rather than the influence of other factors. This is particularly the case for historical data that have been taken in different site conditions and have not been taken using modern standards and techniques (Brázdil et al., 2010). As mentioned earlier, archival documents are of different nature and qualities. We therefore decided to classify them by their degree of reliability according to a scale ranging between 1 and 4:

- The degree 1: not very reliable historical source (it is impossible to indicate the exact documentary origin). It is particularly the case for HI found in the web.
- The degree 2: information found in scientific books talking about storms without clearly mentioning the sources.
- The degree 3: books, newspapers, reports and eyewitness statements citing historical events and clearly specifying its archival sources.
- The degree 4: is the highest level of reliability. Information is taken in a primary source (e.g., an original archival report talking about a storm written by an engineer in the days following the event).

Although the information classified as a category 1 document is not very reliable, it still gives the information that something happened at a date and is therefore not definitely ignored. Typically this type of document needs to be crosschecked with other documents. As shown in Fig. 2 (to the right), the classification of the data reveals a good reliability of collected information as there are no sources classified in category 1 and less than 10% of the sources are in category 2. It is worth noting that paradoxically, the older the information, the more reliable the archival document is.

3.4 The historical surge dataset

The concern is that it is not always possible to estimate a storm surge or a sea level from the information collected for each event. We focus herein on the reconstruction of some events of the 18th century (1720-1767) where certain HI makes it possible to estimate water levels. As depicted in Fig. 2 (to the right), out of the 73 events, 40 are identified as events causing coastal floods, but not all the sources contain quantitative data or at least some information about water level reached. We selected herein the events with the most information about some characteristics of the event (the water level reached, wind speed and direction and in some cases measured information). Table 3 shows a synthesis of the six events which we will analyze in more detail, showing the tide coefficient (obtained from the SHOM website), some wind characteristics and water levels reached in Dunkirk and other cities. The tide coefficient is a ratio of the semi-diurnal amplitude by the mean spring neap tide amplitude introduced by Laplace in the 19th century and commonly used in France since then. Today, the coefficient 100 is attributed by definition to the semi-diurnal amplitude of equinox springtides of Brest. Therefore the range of the coefficient lies between 20 and 120, i.e. the lowest and highest astronomical tides. Calculated for each tide at Brest harbor, it is applied to the complete French metropolitan Atlantic and Channel coastal zone (Simon, 2007). As with the short-term HI, a description of these events which are quite well documented in the literature is presented in Appendix 2 with a description of some other historical events (of which the available information did not allow an estimate of a storm surge value). Some other HI about other extreme storms, occurring in the period 1767-1897, were collected in the archives and identified as events causing coastal floods. A description of these events is also presented in Appendix 2. To be able to reduce the CI of the high RLs (the 1000-year one for instance), it is insufficient to have the time window (the historical period), as the observations or estimates of high surges are unknown. A fixed time window and magnitudes of the available high storm surges are required to improve the estimates of probabilities of failure. The exhaustiveness assumption of the HI on this time window will therefore be too crude and will make no sense. The historical period 1770-1897 was therefore eliminated from inference. Fortunately, these discontinuities in the historical period can be managed in the FM (Hamdi et al, 2015). Two non-successive time windows, 1720-1770 and 1897-2015, will therefore be used as historical periods in the inference.

The extreme storm surges that occurred during the 1720–1767 time-window are then analyzed and the development of a methodology to estimate the surges induced by the events from the last part of the 18th and the 19th century is undergoing. Table 3 shows estimated water levels (for Dunkirk, Gravelines, Calais, Oostende and Nieuport) compared to the associated Mean High-Water Springs (MHWS) which is the highest level reached by springtides (on the average over a period of time often equal to 19 years). De Fourcroy D-R. (1780) presented the water levels in royal foot of Paris, where 1 foot corresponds to 0.325 m and is divided into 12 inches (1 inch = 0.027m) except for the Oostende levels that are given in Flemish Austrian Foot (corresponding to 0.272m and divided in 11 inches). As a first approach the height of the surge above the MHWS level was estimated, which has the advantage that the local reference level does not need to be transposed into the French leveling system and as the historic sea level is considered, there is no need to assess sea level rise which due to climate change can be discarded. De Fourcroy D-R. (1780) gave water levels for the five cities in their respective leveling system: In Calais, zero corresponds to a fixed point on the Citadelle sluice, in Gravelines, zero corresponds to a fixed point on the sluice of the river Aa. For Dunkirk, the “likely low tide of mean springtides” is considered as a zero point and marked on the docks of the Bergues Sluice; we will subsequently refer to this zero as Bergues Zero. The location of the measure point of the Bergues Sluice is presented in Fig. 1 (to the right) on an old map of Dunkirk city. The difference between the observed water levels and the MHWS is the surge above MHWS. The three levels are about the same height, ranging from 1.46m to 1.62m. We calculated the surge above MHWS for Calais, Gravelines, Nieuport and Oostende; they are shown in the second-to-last column of Table 3. It is interesting to note that, for the 1763 and 1767 events, the highest levels were reconstructed in Oostende and the lowest levels in Calais.

For the sake of convenience and for more precision, we needed to transform the surges above MHWS presented in the second-to-last column of Table 3 into skew surges. This refinement required the development of a tide coefficient-based methodology. Indeed, the tide coefficient for each storm event indicates whether surge above MHWS is over- or underrated or approximately right. As this coefficient is calculated for the Brest site and applied to the whole coastal zone, a table showing expected mean levels in Dunkirk for each tide coefficient was established. One tide coefficient estimated at Brest can have different highwater levels at Dunkirk. For this study, it was assumed that the historic MHWS corresponds to the tide coefficient 95. In the developed methodology, all the 2016 hightides for each tide coefficient are used and the water levels for each tide coefficient are averaged. The difference Δ_{WL} between this averaged level and the water level corresponding to the tide coefficient 95 (the actual MHWS) is then calculated and added (or subtracted) to the historic surge above MHWS. Where we have two surges, the mean of the two values is considered. Results for the Dunkirk surges are shown in the last column of Table 4.

In addition to the water levels reached during events and in specific years, other types of HI (lower bounds and ranges) can be collected. For instance, De Fourcroy D-R. (1780) stated that the highest water level measured during the period 1720-1767 was the one induced by the 1767 extraordinary storm. Paradoxical though it may seem at first sight, the skew surge caused by the 1763 storm is greater than the 1767 one. A plausible explanation is that the 1767 event occurred when the tide was higher than that of 1763. Fig. 3 shows two examples of HI collected in the archives.

For the Dunkirk series, it is interesting to see that it is easier to estimate storm surges induced by events from the 18th century, as the water levels were either measured or reconstructed only a few years after the events took place. During research for his thesis, N. Pouvreau (2008) started an inventory of existing tide gauge data available in different archive services in France. According to him, the first observations of the sea level in Dunkirk were made in the years 1701 and 1702, where time and height were reported. Observations were also made in 1802 and another observation campaign was held during 1835. The first longer series dates from 1865 to1875. For the 20th century, only sparse data is available for the first half of the century. Pouvreau (2008) only listed the data found in the archives of the National Geographic Institute (Institut Géographique National IGN), the Marine Hydrographic and Oceanographic Service (Service Hydrographique et Océanographique de la Marine SHOM) and the Historical Service of Defense (Service Historique de la Défense SHD). During the present study we found evidence that sea levels were measured at the Bergues sluice during the 18th century and that various hydrographic campaigns were carried out during the 19th century (De Fourcroy D-R., 1780). This research and first analysis of historical data shows the potential of the data collected, as we were able to quantify some historical skew surges, but it also shows how difficult and time-consuming the transformation of descriptive information into skew surge values is, and that more detailed analysis will be necessary to estimate the other historical surges.

4 Frequency estimation of extreme storm surges using HI

In this work, we suggest a method of incorporating the HI developed by Hamdi et al. (2015). The proposed FM (POTH) is based on the Peaks-Over-Threshold with HI. The POTH method uses two types of HI: Over-Threshold Supplementary (OTS) and Historical Maxima (HMax) data which are structured in historical periods. Both kinds of historical data can only be complementary to the main systematic sample. The POTH FM was applied to the Dunkirk site to assess the value of historical data in characterizing the coastal flooding hazard and more particularly in improving the frequency estimation of extreme storm surges.

4.1 Settings of the POT frequency model

To prepare the systematic POT sample and in order to exploit all available data separated by gaps, the surges recorded since 1956 were concatenated to form one systematic series. However, it makes for subjectivity in what should be taken as a reasonable threshold for the POT frequency model. Indeed, the use of a too-low threshold can introduce a bias in the estimation by using observations which may not be extreme data, which violates the principle of the extreme value theory. On the other hand, the use of a too-high threshold will reduce the sample of extreme data. Coles (2001) has shown that stability plots constitute a graphical tool for selecting the optimal value of the threshold. The stability plots are the estimates of the GPD parameters and the mean residual life-plot as a function of the threshold when using the POT approach. It was concluded that a POT threshold equal to 0.75m (corresponding to a rate of events equal to 1,4 events/year) is an adequate choice. The POT sample with an effective duration w_s of 46,5 years (from 1956 to 2015) is represented by the grey bars in the left panel of Fig. 4 (a, b and c). As homogeneity, stationarity and randomness of time series are prerequisites in a FA (Rao & Hamed, 2001), non-parametric tests such as the Wilcoxon test for homogeneity (Wilcoxon, 1945), the Kendall test for stationarity (Mann, 1945), and the Wald-Wolfowitz test for randomness (Wald & Wolfowitz, 1943) are applied. These tests were passed by the Dunkirk station at the 5% level of significance.

4.2 The POTH frequency model

The HI is used in the present paper as HMax data. A HMax data period corresponds to a time interval of known duration w_{HMax} during which historical n_k-largest values are available. Periods are assumed to be potentially disjoint from the systematic period. The distribution of the HMax exceedances is assumed to be a Generalized Pareto one (GPD). The observed distribution function of HMax and systematic data are constructed in the same way with the Weibull rule. To estimate the distribution parameters by using the maximum likelihood technique in the POTH model, let us assume a set of POT systematic observations $X_{sys,i}$ with a set of historical HMax surges $X_{HMax,i}$ and assume that the systematic and historical storm surges are available with a density function $f_X(.)$. Under the assumption that the surges are iid, the global likelihood function of the whole data sample is any function $L(G|\underset{\leftrightarrow}{\theta})$ proportional to the joint probability density function $f_X(.)$ evaluated at the observed sample and it is the product of the likelihood functions of the particular types of events and information. The global log-likelihood can be expressed as

$$\ell\left(G\,|\,\underset{\leftrightarrow}{\theta}\right)=\overbrace{\ell\left(X_{sys,i}\,|\,\theta\right)}^{systematic\ data}+\overbrace{\ell\left(X_{HMax,i}\,|\,\theta\right)}^{HMax\ data} \qquad (1)$$

Let us assume a set of n POT systematic observations X_i and a selected threshold u_s and consider w_s the total duration. For a Homogeneous Poisson Process with rate λ, the log-likelihood $\ell\left(X_{sys,i}\,|\,\theta\right)$ is

$$\ell\left(X_{sys,i}\,|\,\theta\right)=n\log\left(\lambda w_s\right)-\log\left(n!\right)-\lambda w_s+\sum_{i=1}^{n}\log f\left(X_{sys,i},\theta\right) \qquad (2)$$

For the HMax data, it takes the form

$$\ell\left(X_{HMax,i}\,|\,\theta\right)=n_k\log\left(\lambda w_{HMax}\right)-\lambda w_{HMax}\left[1-F\left(X_k,\theta\right)\right]+\sum_{i=1}^{n_k}\log f\left(X_{HMax,i},\theta\right) \qquad (3)$$

The reader is referred to Hamdi et al. (2015) for more details about each term of these expressions.

4.3 Settings of the frequency model with HI (POTH)

An important question arises with regard to the exhaustiveness of the HI collected in a well-defined time window (called herein the historical period). In order to properly perform the FA, this criterion must be fulfilled. Indeed, we have good evidence to believe that other than the 1995 storm surge, the surges induced by the 1897, 1949 and 1953 storms are the biggest for the period 1897-2015. The POTH FM was first applied with a single historical datum which is that of 1953 represented by the red bar in Fig. 4-a. It not complicated to demonstrate that this event is undoubtedly an outlier. Indeed, in order to detect outliers, the Grubbs-Beck test was used (Grubbs and Beck, 1972). As mentioned in the previous section, some historical extreme events experienced by Dunkirk city are available in the literature. Only this information (including the 1953 event) is considered in this first part of the case study.

Otherwise, HI is most often considered in the FA models for pre-gauging data. Less or no attention has been given to non-recorded extreme events that occurred during the systematic missing periods. As mentioned earlier in this paper, the sea level measurement induced by the 1995 storm was missed and a value of the skew surge (1.15m) was reconstructed from information found in the literature (Maspataud, 2011). As this event is of ordinary intensity and has taken place very recently, it is considered as systematic data even if this type of data can be managed by the POTH FM by considering it as HI (Hamdi et al, 2015). The HI collected from both literature and archives with some model settings are summarized in Table 5 and the POTH sample with a historical period of 72.51 years is presented in Fig. 4-b. Parameters characterizing datasets including both systematic and HI were introduced in Hamdi et al, (2015). The HI is used herein as HMax data that complements the systematic record (with an effective duration D_{eff} equal to w_s) on one historical period (1897-2015) with a known duration $w_h = w_{HMax} = 2015-1897+1-D_{eff}$ ($w_h = 72,51\,years$) and three historical data ($n_k = 3$). Other features of the POTH FM have been used. A parametric method (based on the Maximum Likelihood) for estimating the Generalized Pareto Distribution (GPD) parameters considering both systematic and historical data have been developed and used. The maximum likelihood method was selected for its statistical features especially for large series and for the ease with which any additional information (i.e. the HI) is incorporated in it. On the other hand, the plotting positions exceedance formula based on both systematic observations and HI (Hirsch, 1987; Hirsch and Stedinger, 1987; Guo, 1990) is proposed to calculate the observed probabilities and has been incorporated into the POTH FM considered herein. The reader is referred to Hamdi et al. (2015) for more theoretical details on the POTH model and on the Renext package used to perform all the estimations and fits.

5 Results and discussion

We report herein the results of the FA applied to the Dunkirk tide gauge. As with any sensitive facility, high Return Levels (RLs) (100, 500 and 1000-year extreme surges, for instance) are needed for the safety of NPPs. The results are presented in the form of probability plots in the right panel of Fig. 4 (d, e and f). The theoretical distribution function is represented by the solid line in this figure, while the dashed lines represent the limits of the 70% CIs. The HI is depicted by the empty red circles, while the black full ones represent the systematic sample. The results (estimates of the desired RLs and uncertainty parameters) are also summarized in Table 6. Fitting the GPD to the sample of extreme POTH storm surges yields the relative widths $\Delta CI/S_T$ of the 70% CIs (the variance of the RL estimates are calculated with the delta method).

The FA was firstly performed considering systematic surges and the 1953 storm surge as historical data. It can be seen that the fit of the POTH sample including the 1953 historical event (with w_h equal to 16.5 years) presented in Fig. 4-d (called hereafter the initial fitting), is poor at the right tail and more specifically, at the largest storm surge (the historical data of 2.13 m occurred in 1953) which have a much lower observed return period than its estimated one. The estimates of the RLs of interest and uncertainty parameters (the relative width $\Delta CI/S_T$ of the 70% CIs) are presented in columns 2-3 of Table 6. These initial findings are an important benchmark as we follow the evolution of the results to evaluate the impact of additional HI. 100-, 500- and 1000-year quantiles given by the POTH FM with the 1897, 1949 and 1953 historical storm surges included are about 3-6% higher than those obtained by the initial POTH FM. This result was expected as the additional historical surges are higher than all the systematic ones. The relative widths of the CIs are about 20-25% narrower.

Unlike the 1897 historical event, the 1949 and 1953 ones have a lower observed return period than their estimated one. A plausible explanation for this result is that the body of the distribution is better fitted than the right tail one and this is a shortcoming directly related to the exhaustiveness assumption used in the POTH FM. Indeed, as stated in Hamdi et al. (2015) and as mentioned above, a major limitation of the developed FM arises when the assumption related to the exhaustiveness of the information is not satisfied. This is obviously worrying for us because the POTH FM is based on this assumption. Overall, using additional data in the local FM has improved the variances associated with the estimation of the GPD parameters but did not conduct to robust estimates with a better fitting (particularly at the right tail, the high RLs being very sensitive to the historical values) if the assumption of exhaustiveness is still strong. This first conclusion is likewise graphically backed by the CIs plots shown in Fig. 4-e. Nevertheless, as the impact of historical data becomes more significant, there is an urgent need to carry out a deeper investigation of all the historical events that occurred in the region of interest (Nord-Pas-de-Calais) over the longest historical period. In order to have robust estimates and reduced uncertainties, it is absolutely necessary that the collected information be as complete as possible.

The robustness of the POTH FM is one of the more significant issues we must deal with. The main focus of this discussion is the assessment of the impact of the additional HI (collected from the archives) on the frequency estimates for high RLs. The same FM was performed but with the long-term additional HI (collected in the archives) and different settings (Table 5). The results of the POTH FM using HI from both literature and archives (called hereafter the full FM) are likewise summarized in the last two columns of Table 6. The results are also presented in the form of a probability plot (Fig. 4-f). Fig. 7 consists of two subplots related to the FA of the Dunkirk extreme surges. The left side (Fig. 4-c) shows collected data: the systematic surges are represented by the grey bars, the historical surges extracted from the literature by red bars and those extracted from the archives (estimated and corrected with regards to the tide coefficients) are represented by the green ones. We can also see the two time windows (the blue background areas in the graph) 1720-1770 and 1897-2015 used in the POTH FM as historical periods. The right side shows the results of the full FM. As mentioned earlier in this paper, to consider the full POTH FM, six historical storm surges distributed equally ($n_k = 3$) over two not-successive time windows: 1720-1770 ($w_{HMax1} = 50$ *years*) and 1897-2015 (w_{HMax2} = 72.5 years, knowing that w_s = 46.5 years) are used as historical data. In the plotting positions, the archival historical surges are represented by green squares, while those found in the literature are depicted by red circles. The fitting presented in Fig. 4-f shows a good adequacy between the plotting positions and theoretical distribution function (calculated probabilities of failure). Indeed, all the points of the observed distribution are not only inside the CI, but even better, they are almost on the theoretical distribution curve. The results of Table 6 show that:

- The RLs of interest had increased by only 10 to 20 cm. This is an important element of robustness. Indeed, adding or removing one or more extreme values from the dataset does not significantly affect the desired RLs. In other words, it is important that the developed model is not very sensitive (in terms of RLs used as design bases) to a modification in the data regarding very few events. As a matter of fact, the model owes this robustness to the exhaustiveness of the available information.
- The relative widths of CIs with no archival HI included are 1.5 times larger than those given by the full model. This means that the user of the developed model is more confident in the estimations when using the additional HI collected in the archives.

After collecting HI about the most extreme storm surge events in the 18th and 20th centuries, it was first found that the 1953 event is still the most important one in terms of magnitude. The developed POTH FM attributed a 200-year return period to this event. The value of the surge induced by the 1953 storm is between 1.75m and 2.50m. That said, it is interesting to note that this CI includes the value of 2.40m estimated by Le Gorgeu and Guitonneau (1954). This may be a reason to think that the continuation of our work on the quantification of the skew surges that occurred in the 19th century will perhaps reveal extreme surges similar to that induced by the 1953 storm.

6 Conclusion & perspectives

To improve the estimation of risk associated with exceptional high surges, HI about storms and coastal flooding events for the Nord-Pas-de-Calais was collected by historians for the 1500-1950 period. Qualitative and quantitative information about all the extreme storms that hit the region of interest were extracted from a large number of archival sources. In this paper, we presented the case study of Dunkirk in which the exceptional surge induced by the 1953 violent storm appears as an outlier. In a second step, the information collected (in both literature and archives) was examined. Quality control and cross validation of the collected information indicate that our list of historic storms is complete as regards extreme storms. Only events that occurred in the periods 1720-1770 and 1897-2015 were estimated and used in the POTH FM as historical data. To illustrate challenges and opportunities for using this additional data and analyzing extremes over a longer period than was previously possible, the results of the FA of extreme surges was presented and analyzed. The assessment of the impact of additional HI is carried out by comparing theoretical quantiles and associated confidence intervals, with and with no archival historical data, and constitutes the main result of this paper.

The conclusions drawn in previous studies were examined in greater depth in the present paper. Indeed, on the basis of the results obtained previously (Hamdi et al, 2015) and in the present paper, the following conclusions are reached:

- The use of additional HI over longer periods than the gauging one, can significantly improve the probabilistic and statistical treatment of a dataset containing an exceptional observation considered as an outlier (i.e. the 1953 storm surge).
- As the HI collected in both literature and archives tend to be extreme, the right-tail distribution has been reinforced and the 1953 “exceptional” event does not appear as an outlier any more.
- As this additional information is exhaustive (relatively to the corresponding historical periods), the RLs of interest increased very slightly and the confidence intervals were reduced significantly.

An in-depth study could help to thoroughly improve the quantification method of the historical surges and apply the developed model on other sites of interest. Finally, an attempt is undergoing to carry out the estimation of the surges induced by the events from 1767 to the end of the 19th century is undergoing.

Appendix 1: HI collected in the literature

<u>01/03/1949:</u> A violent storm with mean hourly wind speeds reaching almost $30 m.s^{-1}$ and gusts of up to $38.5 m.s^{-1}$ (Volker, 1953) was the cause of a storm surge that reached the coast of Northern France and Belgium in the beginning of March 1949. The tide gauge of Antwerp in the Escaut estuary measured a water level higher than 7m TAW (a reference level used in Belgium for water levels) which classifies this event as a “*buitengewone stormvloed*”, an extraordinary storm surge (Codde and De Keyser 1967). For the Dunkirk area two sources reporting water levels were found: the first saying that 7.30m was reached as a maximum water level at the eastern Dike in Dunkirk, exceeding the predicted hightide, i.e. 5.70m, with 1.60m (Le Gorgeu and Guittoneau 1954). A second document relates that the maximum water level reached was about 7.55m at Malo-les-Bains, which would mean a surge of 1.85m (DREAL Nord-Pas-de-Calais). It is worth noting that the use of proxy data (i.e. the descriptions of events in the historical sources summarized in Table 1) to extract sea-level values and to create storm-surge databases is seriously limited. For the 1791 and 1808 storms, there is sufficient evidence that extreme surge events took place (extreme water level on Walcheren Island) but the sources are not informative enough to estimate water levels reached in Dunkirk. A surge of 1.25m is given for the storm of 1921. The problem is that the type of surge (instantaneous or skew), the exact location at which it was recorded and the hydro-meteorological parameters are not reported. For the skew surge of 1949, two different values at two locations are given. There are predicted and observed water levels for the storms of 1905 and 1953 in Calais, which indicate that the difference is a skew surge, but likewise neither the exact location nor the information about the reference level are furnished. The need for tracing back to “direct data” describing a storm and its consequences becomes clear, as well as performing a cross-check of the data on a spatial and factual level, as Brázdil (2000) also suggests.

<u>28/11/1897:</u> What was felt as stormy winds in Ireland on November 27th, 1897 became an eastward-moving storm with gale-force winds over Great Britain, Denmark and Norway (Lamb, 1991). This storm caused interruption of telephone communications between the cities of Calais, Dunkirk and Lille and great damage to the coastal areas (Le Stéphanois, November 30th, 1897). At Malo-les-Bains, a small town close to Dunkirk, the highest water level reached 7.36m although the hightide was predicted at 5.50m, resulting in a skew surge of 1.86m that caused huge damage to the port infrastructures (DREAL Nord-Pas-de-Calais).

<u>14/01/1808:</u> During the night from January 14th to 15th, 1808, “a terrible storm, similar to a storm that hit the region less than one year before on February 18, 1807” hit the coasts of the most northern parts of France up to the Netherlands. This storm caused severe flooding as well in the Dunkirk area as in the Zeeland area in the south western parts of the Netherlands where the water rose up to 25 feet on the isle of Walcheren (i.e. 7.62m). The journal also reports more than 200 deaths. For the Dunkirk area, the last time the water levels rose as high as in January 1808 was February 2nd, 1791. Unfortunately, this source does not provide any information that we can quantify or any information on the meteorological and weather conditions that we can use to reconstruct the storm surge value.

Appendix 2: HI collected in the archives

1720-1767: In essays written by a mathematician of the royal academy of science, De Froucroy D-R, who describes the tide phenomenon on the Flemish coast, some extreme water levels observed within the study area are reported and described. The author refers to five events that occurred during the period 1720 to 1767. The same information is confirmed by a Flemish scientist, Dom Mann (1777, 1780). De Froucroy D-R witnessed the water levels induced by the 1763 and 1767 storms and reconstructed the level induced by the 1720 event in Dunkirk. Water levels at that time are given for the cities of Dunkirk, Gravelines and Calais in the "pied du roi" unit ("foot of the king" was a French measuring unit, corresponding to 0.325m) above local mean low-water springs. The French water levels are completed by measurements made in ancient Flemish feet above the highest astronomical tides for the cities of Oostende and Nieuport (De Fourcroy D-R., 1780; Mann, 1777, 1780). The upper panel of Fig. 3 shows an example of HI as presented in the archives (De Fourcroy D-R., 1780).

The 1720 event is a memorable event for the city of Dunkirk, as the water level during springtide was increased by the strong gales blowing from north-western direction which destroyed the cofferdam built by the British in the year 1714, cutting the old harbor off from sea access and prohibiting any maritime trade, thus slowly causing the ruin of the city. The socio-cultural impact of the natural destruction of the cofferdam was huge, as it restarted trading in the city (Chambre de Commerce de Dunkerque 1895, Plocq, 1873, Belidor, 1788). In 1736, the only sea level available is given for Gravelines harbor, but extreme water levels are confirmed in the sources as they mention at least 4 feet of water in a district of Calais, and water levels that overtopped the docks of the harbor in Dunkirk (Municipal Archive of Dunkirk DK291, Demotier, 1856). As mentioned above, communal and municipal archives contain plans of dykes, docks and sluices in Dunkirk harbor designed by engineers with the means available at that time, and such sketches were recovered. A 1740 sketch showing a profile of the Dunkirk harbor dock is presented in the lower panel of Fig. 3 for illustrative purposes only. The use of these plans and sketches in the estimation of some historical storm surges is ongoing. The lower-lying streets of Gravelines were accidently flooded by the high water levels in March 1750. The fact that an extreme water level was also reported in Oostende for the same day confirms the regional aspect of the event. The surge of 1763 occurred in a period with mean tidal range, but water level exceeded the level of mean spring hightide in Dunkirk, Calais and Oostende. Unfortunately no more information about the flooded area is available. Strong west-north-westerly winds caused by a quick drop in pressure produced high water levels from Calais up to the Flemish cities. It is, at least for the period from 1720 to 1767, the highest water level ever seen and known. The 1720 and 1767 events show good evidence of the wind direction and wind intensity, while in various sources, except for the water levels reported, the events from 1736, 1750 and 1763 are always cited together and described as "*extraordinary sea-levels that are accompanied or caused by strong winds blowing from South-West to North"* (De la Lande, 1781, De Fourcroy D-R., 1780, Mann, 1777, 1780). As with the 1897-2015 historical/systematic periods, the same question related to the exhaustiveness of the HI collected in the 1720-1770 historical period arises. As our historical research on extreme storm surges occurred in this time window was very thorough, we have good reasons to believe that the surges induced by the 1720, 1763 and 1767 storms are the biggest for that historical period.

1767–1897: For the 1778, 1791, 1808 and 1825 events, the sources report strong that winds were blowing from north-westerly directions and that in Dunkirk the quays and docks of the harbor were overtopped as the highest water levels were reached. We know that, after the event of February 1825, at least 19 storm events occurred and we have good evidence to believe that some of them induced extreme surges, but either the information available is not sufficient to draw an approximate value of the water level, or the quantification of the storm surges induced by these events is complicated and time-consuming.

1936: The 1936 event can be considered as a lower bound, as the document from the archive testifies that the "water level was at least 1m higher than the predicted tide" during the storm that occurred on the night of December 1st, 1936 (Municipal Archives of Dunkirk 4S 881). The 1936 event, which can be described as a moderately extreme storm, is the only one collected on the 50-year time window (1897-1949). As the surge lower bound value induced by this event is too small (i.e. exceeded more than 10 times during the systematic period), it could be exceeded several times during the 1897-1949 period. Its involvement in the statistical inference will have the opposite effect and will not only increase the width of the CI but will also degrade the quality of the fit. The 1936 historical event was therefore eliminated from inference.

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Table 1 Date, localization, water and surge levels (m) of collected storms within Nord-Pas-de-Calais area.

Date	Location	Predicted WL	Observed WL	Surge	Source
28/11/1897	Malo-les Bains Dunkirk	5,50[1]	7,36[1]	1,86[1]	DREAL Nord – Pas de Calais
01/03/1949	Dunkirk	5,70 NGF	7,30 NGF[2]	1,60	Le Gorgeu & Guitonnau, 1954
			7,55 NGF[2]	1,85	DREAL Nord–Pas de Calais
01/02/1953	Antwerpen (BE)	- - -	> 7 TAW[3]	- - -	Codde and De Keyser 1967
	Sangatte, Calais	6,70	8,20	1,50	Deboudt, 1997
	Dunkirk	5,50	7,90	2,40	Le Gorgeu & Guitonnau, 1954
	Dunkirk	5,77	7,90	2,13	Bardet et al., 2011

[1] no reference leveling given; [2] NGF : the French Ordnance Datum (Nivellement Général Français); [3] TAW = Tweede Algemeene Waterpassing(a reference level used in Belgium for water levels); [4] no indication which feet (royal french feet / flemish austrian feet); [5] Newspapers: Journal Politique de Mannheim 26, 30 Janvier 1808 ;

Table 2 Details of 1500-2015 Nord-Pas-de-Calais historical storms and storm surges sources.

Year/Date	Data Type	Quality Index	Source Name	Observer occupation
1507	Surge	3	L'Abbé Harrau (1901)	Historian
01/11/1570	Surge	3	Pierre Faulconnier (1730)	Mayor of Dunkirk
1605	Surge	3	Victor Derode (1852)	Historian
12/01/1613	Surge	4	MAS-O (XVIIIth century) - Jean Hendricq bourgeois	Bourgeois and merchant of the city
01/11/1621	Surge	4		
03/11/1641	Surge	3	Céléstin Landrin (1888)	Archivist (Calais)
1644	Surge	4	M. Lefebvre (1766)	Priest
1663	Surge	3	Victor Derode (1852)	Historian
12/1663	Surge	3	Baron C. de Warenghien (1924)	Historian
1665	Surge	3	Victor Derode (1852)	Historian
1671	Surge	3		
1675	Surge	3		
16/02/1699	Surge	3	L'abbé Harrau (1903)	Historian
1715	Surge	3	Victor Derode (1852)	Historian
1720	Surge	3		
31/12/1720	Surge	4	De La Lande (1781)	Astronomer
25/12/1730	Storm	3	Charles Demotier (1856)	Local Historian
1734	Surge	4	MAD (AncDK15)	Unknown
19/01/1735	Storm	4		
27/02/1736	Surge	4	MAD, (AncDK291)/C. Demotier (1856)	Historian
01/10/1744	Storm	3	Jean Louis le Tellier (1927)	Local of Dunkirk
11/03/1750	Surge	3	De La Lande (1781)	Astronomer
06/07/1760	Storm	3	Almanach de Calais (1845)	Unknown
02/12/1763	Surge	3	De La Lande (1781)	Astronomer
28/09/1764	Surge	2	J. Goutier «Amis du Vieux Calais»	Unknown
02/01/1767	Surge	3	M.A. Bossaut (1898)	Librarian
05/1774	Surge	4	MAD, ref. 2 Fi 169	Unknown
01/01/1777	Surge	3	Raymond de Bertrand (1855)	Writer
01/01/1778	Storm	3	Leon Moreel (1931)	Lawyer
31/12/1778	Surge	4	Pigault de Lespinoy, 19th cent. - a	Mayor of Calais
02/02/1791	Surge	4	Pigault de Lespinoy, 19th cent. - b	
17/11/1791	Surge	2	Bernard Barron (2007)	Journalist
04/09/1793	Surge	3	L'abbé Harrau (1898)	Historian
30/10/1795	Storm	3	Céléstin Landrin (1888)	Archivist (Calais)
13/11/1795	Storm	3	Charles Demotier (1856)	Historian
09/11/1800	Storm	4	MAD, ref. 2Q9	Unknown
29/03/1802	Storm	3	Augstin Lemaire (1857)	Regent
03/11/1804	Storm	3	Augstin Lemaire (1857)	Regent
1807	Surge	3	Victor Derode (1852)	Historian
18/02/1807	Storm	3	Mannheim, 26/01/1808	Newspaper
02/12/1807	Storm	3	Augstin Lemaire (1857)	Regent
14/01/1808	Surge	4	MAC, « floods » sheets	Archivists (Dunkirk)
14/11/1810	Storm	2	Christian Gonsseaume (1988)	Historian
03/01/1825	Surge	2	MAC, « storms » sheets	Archivists (Dunkirk)
04/02/1825	Surge	4	MAD, ref. 5O6	Harbor Engineer
19/10/1825	Storm	4	MAC, « storms » sheets	Archivists (Dunkirk)
29/11/1836	Storm	3	Union Faulconnier(1936)	Mayor of Dunkirk
02/01/1846	Surge	3	Victor Derode (1852)	Historian
02/10/1846	Surge	3		
26/09/1853	Storm	3	Dr. Zandyck (1861)	Military Surgeon & Physician
26/10/1859	Storm	3		
02/11/1859	Storm	3		
16/01/1867	Storm	2	Gilles Peltier «Amis du Vieux Calais»	Unknown
02/12/1867	Storm	2	Bernard Barron (2007)	Journalist
30/01/1877	Storm	4	MAC, « storms » sheets	Archivists (Dunkirk)
21/12/1892	Storm	3	Céléstin Landrin (1888)	Archivist (Calais)
10/01/1893	Storm	4	MAD, reference 5 S 1	Harbor Engineer
18/11/1893	Storm	2	Gilles Peltier «Amis du Vieux Calais»	Unknown
11/10/1896	Storm	2	Christian Gonsseaume (1988)	Historian
27/01/1897	Storm	2	Christian Gonsseaume (1988)	Historian
29/11/1897	Surge	4	MAD, reference 4 S 874	Architect Gontier
02/03/1898	Storm	4	Le Gravelinois, (19/03/1989)	Unknown
13/01/1899	Storm	4	Le Nord Maritime, (January, 1899)	Unknown
10/12/1902	Storm	2	Christian Gonsseaume (1988)	Historian
11/09/1904	Storm	3	Emile Bouchet (1911)	Man of Letters
08/01/1928	Storm	2	Christian Gonsseaume (1988)	Historian
07/12/1929	Storm	2	Christian Gonsseaume (1988)	Historian
28/11/1932	Storm	4	MAD, ref. 4 S 881	City council of Dunkirk
01/12/1936	Surge	4		
01/03/1949	Surge	4	La Voix du Nord, 2-4/03/1949	Unknown
01/02/1953	Surge	4	La Voix du Nord, 4-6/02/1953	Unknown
16/09/1966	Surge	4	La Voix du Nord, 17/09/1966	Unknown
02/01/1995	Surge	3	Maspataud A., (2011)	PhD student

MAS-O : Saint-Omer Municipal Archives - Historical collection of Jean Hendricq bourgeois of Saint Omer; MAD : Municipal Archives Dunkirk; MAC : Municipal Archives Calais – thematic sheets

Table 3 HI about water levels in Dunkirk and other cities (unless otherwise stated, Heights are given in French royal foot which corresponds to 0,325m).

Date & N°	Tide Coefficient[1]	The event characteristic	Wind direction	City	Water level (ft)	Surges above MHWS (m)	Source name
31/12/1720							- De Fourcroy D-R. (1780); - Plocq (1873).
1	104-104	Violent storm	NW	Dunkirk	22 ft 3 in**	---	
27/02/1736							- De La Lande, (1781) ; - De Fourcroy D-R. (1780).
2	110-114	Accompanied by strong winds	SW to N	Gravelines	13 ft 2 in**	1,38	
				Calais	> 1767	1,06	
11/03/1750							- De La Lande, (1781) ; - De Fourcroy D-R. (1780); - Mann, D. (1777,1780).
3	115-111	Generally accompanied by strong winds	SW to N	Gravelines	12 ft 2 in	1,05	
				Oostende	13 ft 6 in*	---	
02/12/1763							- De La Lande, (1781) ; - De Fourcroy D-R. (1780); - Mann, D. (1777, 1780)
4	78-81	Generally accompanied by strong winds	SW to N	Dunkirk	22 ft	---	
				Calais	17 ft 2 in	0,57	
				Gravelines	14 ft 2 in	0,97	
				Oostende	14 ft*	1,10	
				Nieuport	14 ft*	0,97	
02/01/1767							- Histoire de l'Académie Royale des Sciences (1767) ; - De Fourcroy D-R. (1780); - Mann, D. (1777, 1780)
5	93-96	Horrible storm	WNW-NNW	Dunkirk	22 ft 6 in	---	
				Calais	18 ft 8 in	1,06	
				Gravelines	15 ft 10 in	1,51	
				Oostende	16 ft*	1,60	
				Nieuport	17 ft 1 in*	1,94	
01/12/1936							- MAD 4S 881
6	99-96	Violent storm		Dunkirk	1 m>pred	---	

[1] Source: SHOM; ** reconstructed water levels; * foot of Brussels (1 ft = 0.273m).

Table 4 Historical skew surges induced by the 1720-1767 events. Heights are given in m.

Date	Tide Coef	Surge above MHWS	Δ_{WL}	Skew surge
1720	104	1,54	-0,17	1,37
1763	78/81	1,46	0,29/0,24	1,75/1,7
1767	93	1,62	0,01	1,63

Table 5 The HI dataset (from literature and archives). Surges are given in m and w_{HMax} and w_s in years.

Year	1720	1763	1767	Events exist ($n_k \neq 0$) but cannot be estimated	1897	1949	1953
Surge (m)	1,37	1,75	1,63		1,86	1,60	2,13
	• HI from archives, $n_k = 3$ • 1720-1770 time-window • $w_{HMax1} = 50$			• HI from archives, $n_k \neq 0$ • 1770-1897 time-window • Not used in the inference	• HI from literature, $n_k = 3$ • 1897-2015 time-window • $w_{HMax2} = 72,5$; $w_s = 46,5$		

Table 6 The T-year quantiles & relative widths of their 70% CI (all the duration are given in years)

T (years)	+1953 event		+ literature HI		+ literature & archives HI	
	$w_{HMax1} = 16,5$		$w_{HMax} = 72,5$		$w_{HMax1} = 50$; $w_{HMax2} = 72,5$	
	S_T	$\Delta CI / S_T$	S_T	$\Delta CI / S_T$	S_T	$\Delta CI / S_T$
100	1,76	40%	1,82	32%	1,84	26%
500	2,46	71%	2,59	56%	2,61	48%
1000	2,86	86%	3,03	69%	3,05	59%

Fig. 1. Map of the location (to the left) and an old plan of the Dunkirk city with the measure point of Bergues Sluice (to the right)

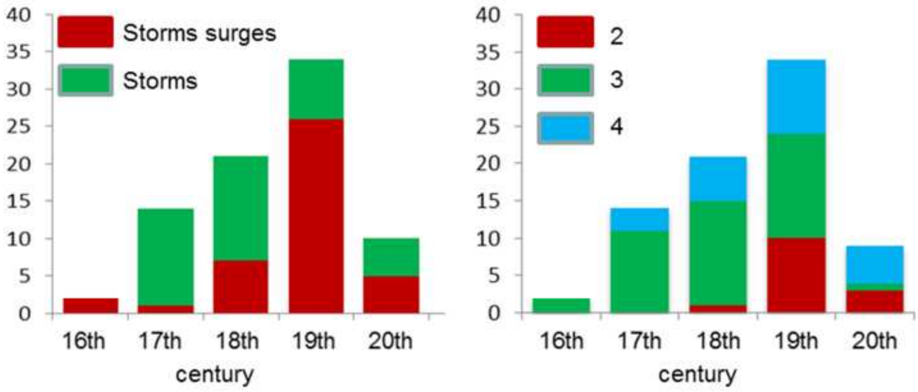
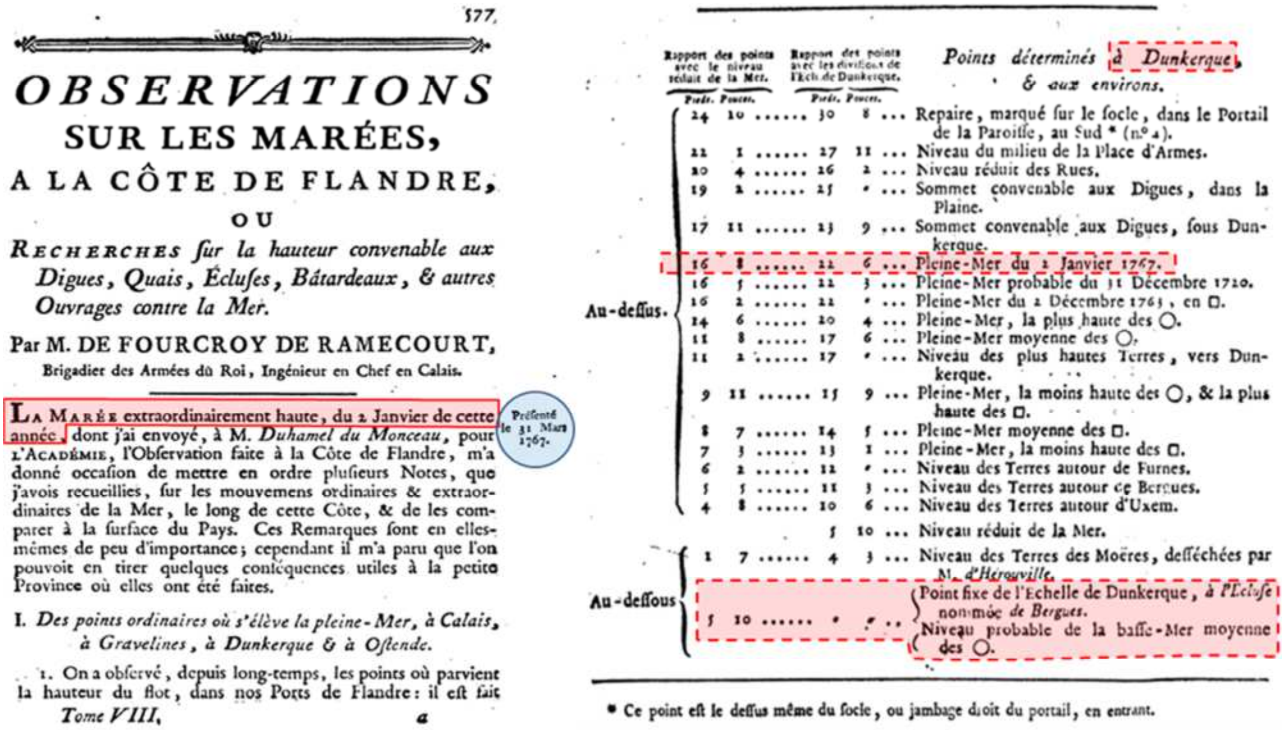


Fig. 2. Distribution in time of the type of the events in the data base (left); Quality of the data (right).



577.

OBSERVATIONS SUR LES MARÉES, A LA CÔTE DE FLANDRE, OU

Recherches ſur la hauteur convenable aux Digues, Quais, Écluſes, Bâtardeaux, & autres Ouvrages contre la Mer.

Par M. DE FOURCROY DE RAMECOURT, Brigadier des Armées du Roi, Ingénieur en Chef en Calais.

Préſenté le 31 Mars 1767.

La Marée extraordinairement haute, du 2 Janvier de cette année, dont j'ai envoyé, à M. *Duhamel du Monceau*, pour l'Académie, l'Obſervation faite à la Côte de Flandre, m'a donné occaſion de mettre en ordre pluſieurs Notes, que j'avois recueillies, ſur les mouvemens ordinaires & extraordinaires de la Mer, le long de cette Côte, & de les comparer à la ſurface du Pays. Ces Remarques ſont en elles-mêmes de peu d'importance; cependant il m'a paru que l'on pouvoit en tirer quelques conſéquences utiles à la petite Province où elles ont été faites.

I. *Des points ordinaires où s'élève la pleine-Mer, à Calais, à Gravelines, à Dunkerque & à Oſtende.*

1. On a obſervé, depuis long-temps, les points où parvient la hauteur du flot, dans nos Ports de Flandre: il eſt fait

Tome VIII, a

	Rapport des points avec le niveau réduit de la Mer. Pieds.	Pouces.	Rapport des points avec les diviſions de l'Ech. de Dunkerque. Pieds.	Pouces.	*Points déterminés à Dunkerque, & aux environs.*
Au-deſſus.	24	10	30	8	Repaire, marqué ſur le ſocle, dans le Portail de la Paroiſſe, au Sud * (n.° 4).
	21	1	27	11	Niveau du milieu de la Place d'Armes.
	20	4	26	2	Niveau réduit des Rues.
	19	2	25	•	Sommet convenable aux Digues, dans la Plaine.
	17	11	23	9	Sommet convenable aux Digues, ſous Dunkerque.
	16	8	22	6	Pleine-Mer du 2 Janvier 1767.
	16	5	22	3	Pleine-Mer probable du 31 Décembre 1720.
	16	2	22	•	Pleine-Mer du 2 Décembre 1763, en □.
	14	6	20	4	Pleine-Mer, la plus haute des ○.
	11	8	17	6	Pleine-Mer moyenne des ○.
	11	2	17	•	Niveau des plus hautes Terres, vers Dunkerque.
	9	11	15	9	Pleine-Mer, la moins haute des ○, & la plus haute des □.
	8	7	14	5	Pleine-Mer moyenne des □.
	7	3	13	1	Pleine-Mer, la moins haute des □.
	6	2	12	•	Niveau des Terres autour de Furnes.
	5	5	11	3	Niveau des Terres autour de Bergues.
	4	8	10	6	Niveau des Terres autour d'Uxem.
			5	10	Niveau réduit de la Mer.
Au-deſſous	1	7	4	3	Niveau des Terres des Moëres, deſſéchées par M. d'Hérouville.
	5	10	•	•	Point fixe de l'Echelle de Dunkerque, *à l'Ecluſe* nommée *de Bergues.* Niveau probable de la baſſe-Mer moyenne des ○.

* Ce point eſt le deſſus même du ſocle, ou jambage droit du portail, en entrant.

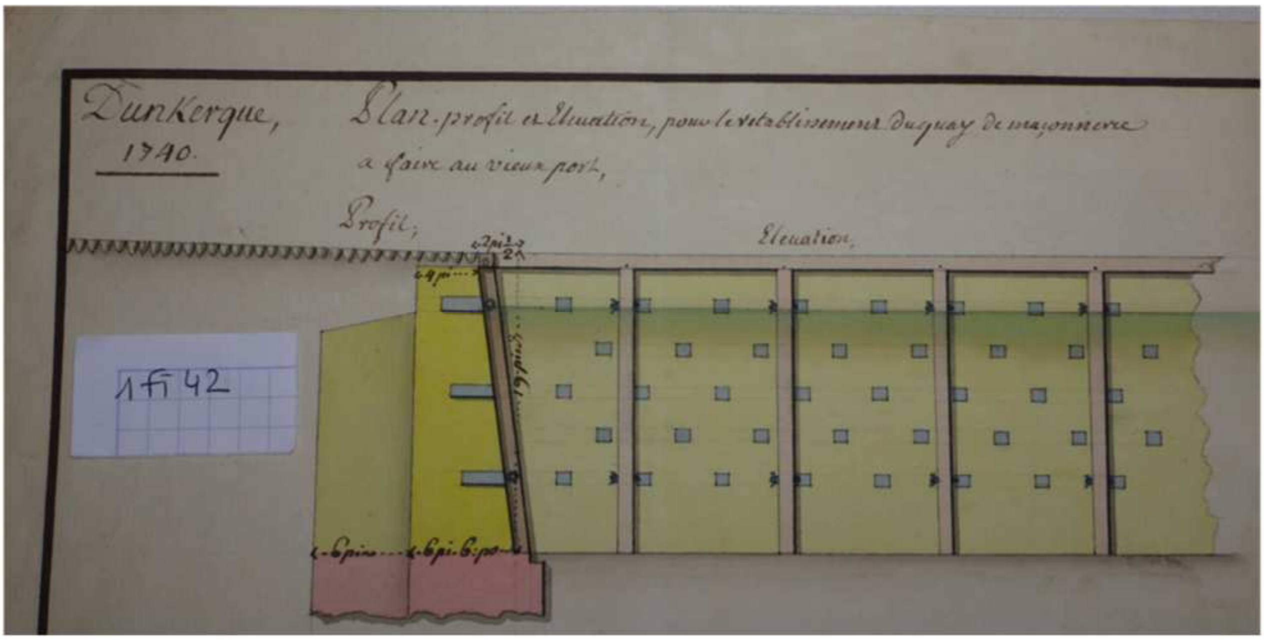


Fig. 3. Two examples of HI as presented in the archives. (Top :) the 1767 extreme storm surge event in Dunkirk (De Fourcroy D-R., 1780); (Bottom :) a profile of the Dunkirk harbor dock from the municipal archives of Dunkirk (ref. 1Fi42, 1740).

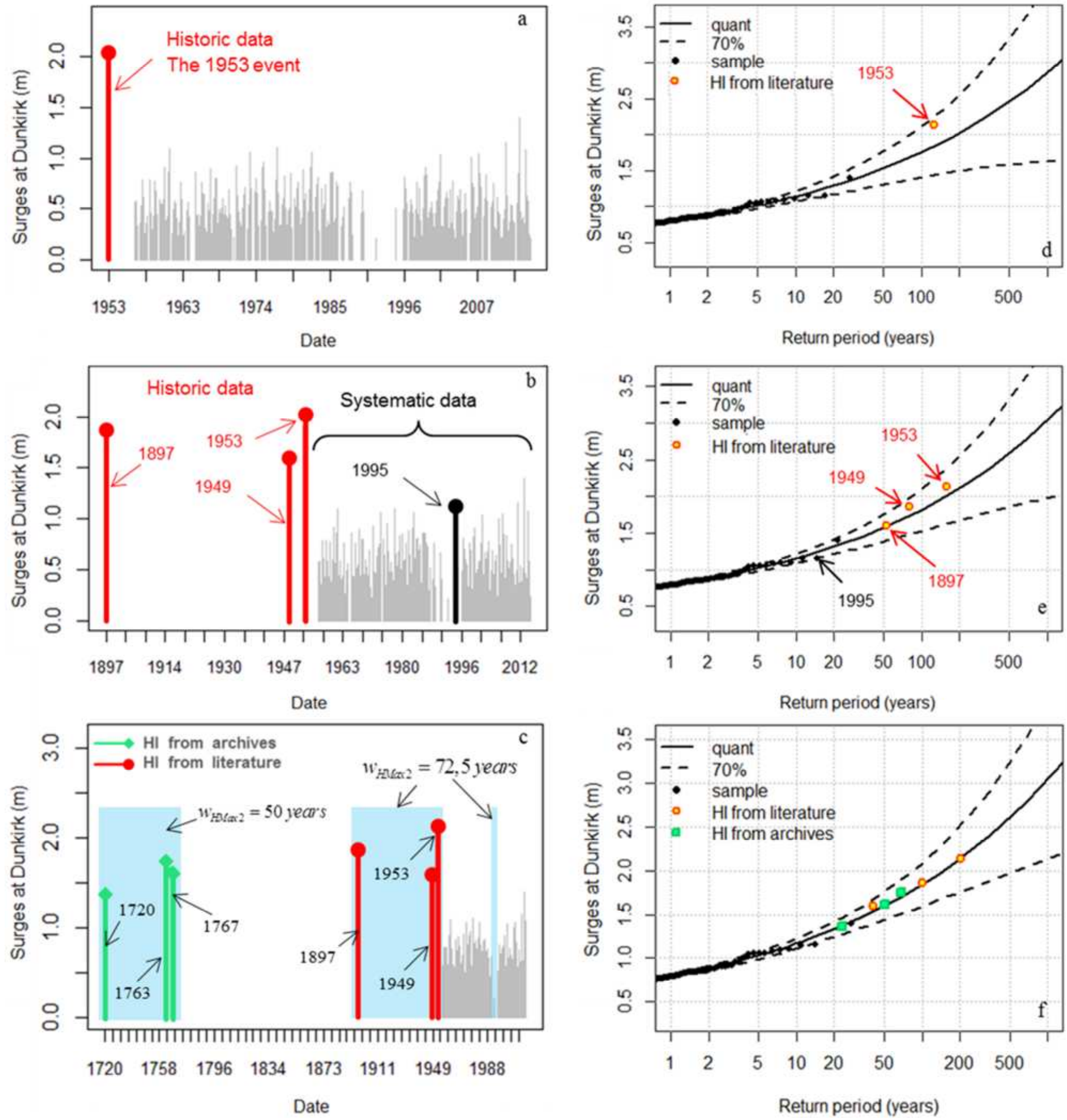


Fig. 4. The GPD fitted to the POTH surges in Dunkirk: (Top :) with the 1953 event as a historical data; (Middle :) with historical data from literature and (Bottom :) with historical data from literature and archives. The 1995 event is considered as systematic.